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American Association *of* Petroleum Geologists

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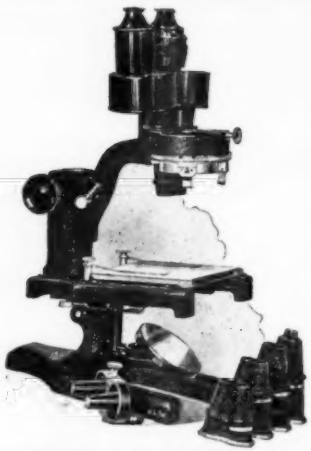

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Volume 15 Number 12

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DECEMBER 1931

UTILIZATION OF EXISTING WELLS IN SEISMOGRAPH WORK[1]

BURTON McCOLLUM[2] and WILTON W. LaRUE[3]
Houston, Texas

ABSTRACT

The writers describe a method of utilizing a well in a seismic exploration of the surrounding area for deep domes, with particular reference to a supposed dome near the well which, for any reason, may have missed its objective. Most of the paper is devoted to methods of utilizing a well near the flank of a salt dome for the purpose of making a seismic profile deep down the flanks. These methods are especially adapted to determining the extent of "mushrooming" such as that existing at Barbers Hill and the Allen dome.

The present economic status of the oil industry, regardless of its cause, is having the effect of directing considerable attention to improved efficiency in prospecting and production methods. In this connection, geophysicists have devoted much thought and effort to developing more accurate means for determining well locations. Some of the more recent seismic methods which have been proved successful are explained here in a qualitative manner with the intention of avoiding burdensome mathematics.

EXPLORING FOR VERY DEEP DOMES

During the past year or more, use has been made of existent wildcat wells for the purpose of making a seismic exploration of the surrounding

[1]Read before the Association at the San Antonio meeting, March 21, 1931. Manuscript received, May 28, 1931. Published by permission of McCollum Exploration Company.

[2]President and technical director, McCollum Exploration Company, Esperson Building. Introduced by George M. Bevier.

[3]Geophysicist, McCollum Exploration Company.

territory for very deep domes. The principle of the method used is shown in Figure 1. Here, a detector of seismic waves is lowered to the bottom

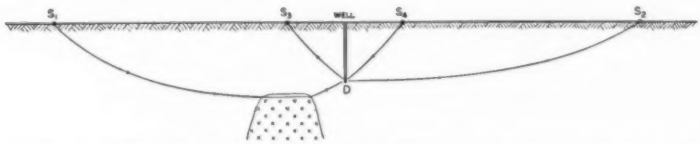


FIG. 1.—Diagram illustrating use of well for exploring surrounding region for deep domes. Patent applied for.

of a wildcat well which may have missed the dome. With the detector in this position, a series of shots is fired on the surface, on a circle having the center approximately at the well and the circumference at a distance ranging from 5 to 7 miles from the well. It is obvious that if a dome exists anywhere within a radius of several miles of the well, as shown in Figure 1, the shots from one direction, as S_1, will show greater velocity than from S_2 and other directions, thereby indicating the presence and position of the dome. If the top of the dome is no more than 2,000 feet below the bottom of the well, actual salt occurrences will be recorded on the detector, thereby giving a very definite lead in the direction of the dome. If the dome is much deeper, however, it can be detected because of the increased velocity in the shale overlying the dome, as this shale is more consolidated and is under abnormally great pressure. In the latter condition, the increase in velocity, especially if the dome is extremely deep, may be small enough so that, in order to make certain of exact shooting distances, it may be necessary to determine whether the bottom of the hole is directly under its surface location. This can be accomplished by the seismograph by shooting four additional shots in four different directions approximately a mile from the well, as indicated by S_3 and S_4 in the section shown in Figure 1. If the bottom of the hole deviates in any direction from vertical, this is revealed by the difference in time of arrival of the sound wave from the four different directions. By this method the direction and amount of drift of the hole can be determined.

It is obvious that by this method the intervening region between the well and the distant shots, particularly that part within 2 or 3 miles of the well, can be explored for deep domes to a depth considerably in excess of the depth of the well used for the detector.

Practical experience with this method has demonstrated its usefulness and there is no doubt that the method can be made very effective in exploring the Gulf Coast for domes to a substantially greater depth

than has heretofore been possible by the usual surface methods of operation. This method has been used only in connection with wildcat wells. It is now proposed greatly to extend its usefulness by utilizing existing wells that have been drilled off the flanks of known domes. Literally hundreds of such wells are available at the present time for this purpose, because any well open to a depth ranging from 4,000 to 6,000 feet, or deeper, can be used. It does not matter whether the well is pumping or whether it is a dry hole. If a flowing well is used, it may be necessary to restrict its flow during the period it is being used for the test. The proposal here is to select any suitable well off the flank of the dome, as at *A* in Figure 2, and, after placing the detector down near the bottom of the

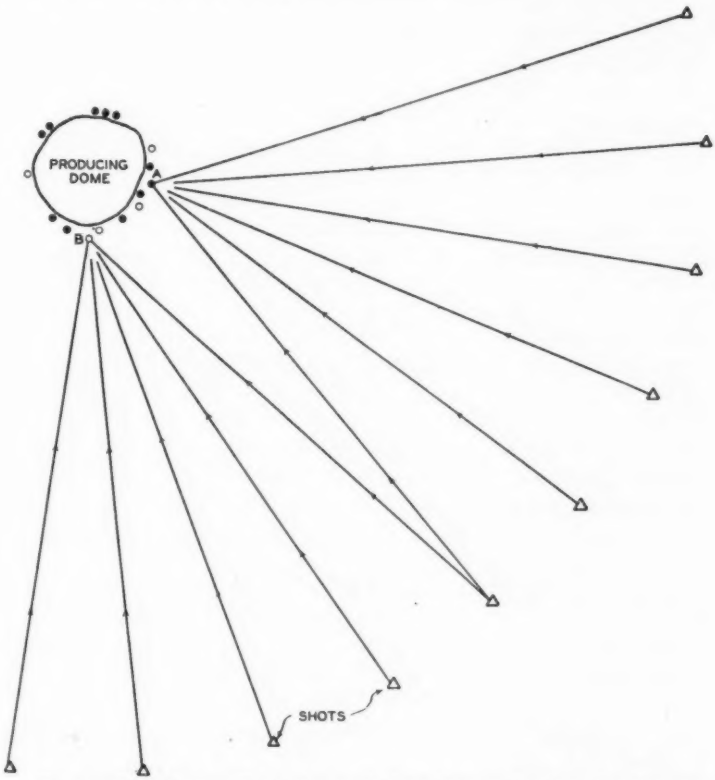


FIG. 2.—Plan diagram illustrating method for deep exploration of region surrounding known domes.

well, shoot a fan of perhaps a 60°-90° angle off the same side of the dome as the well. Then another well, as at *B*, would be used, as shown. On this basis, in order to explore the territory entirely surrounding the dome, it would be necessary to have five or six wells located at suitable places around the dome. It is estimated that by this method a thorough exploration of the entire territory within 3 or 3½ miles from the flank of the known dome can be made down to a depth ranging from 1,000 to 2,500 feet deeper than the depth of the well used in making the test.

Such a deep exploration of the area surrounding known domes might reveal several deep twin domes.

DEEP PROFILING OF SALT DOMES

The problem of profiling deep down the flanks of salt domes has heretofore presented very serious difficulties, and because of these difficulties few attempts have been made to profile more than the top of the dome and that part extending a very short distance over the shoulder. The recent successful use of the described method of placing detectors in wells and exploring the surrounding country for deep domes has opened the way for the development of an accurate method of profiling down the sides of salt domes to depths ranging from 5,000 to 6,000 feet. A method for accomplishing this purpose has always been considered extremely desirable, but it has recently become of vastly greater importance with the discovery of the mushrooming tendency on some salt domes in the Gulf Coast region.

The general method of procedure is simple, as shown by an inspection of Figure 3. Here a shot is placed as shown at some convenient point on the opposite side of the dome from the well which is being used in the exploration; a detector is let down in the well to any suitable position such as D_1, and a shot made. The detector is then lowered in the well to the point D_2, and so on, shots being made with the detector spaced at suitable intervals down to the bottom of the well. It is readily understood that the total time of travel of the shot to different detector positions is a function of the spacing between the well and the salt mass. With a knowledge of the velocity of sound in rock salt and its velocity in the deep shales, together with the geometrical relationships involved, it is possible to calculate the form of the profile of the dome opposite the well with considerable accuracy. In this way it can be determined with certainty whether or not the dome slopes continually outward or whether it recedes with increasing depth, as shown in Figure 3.

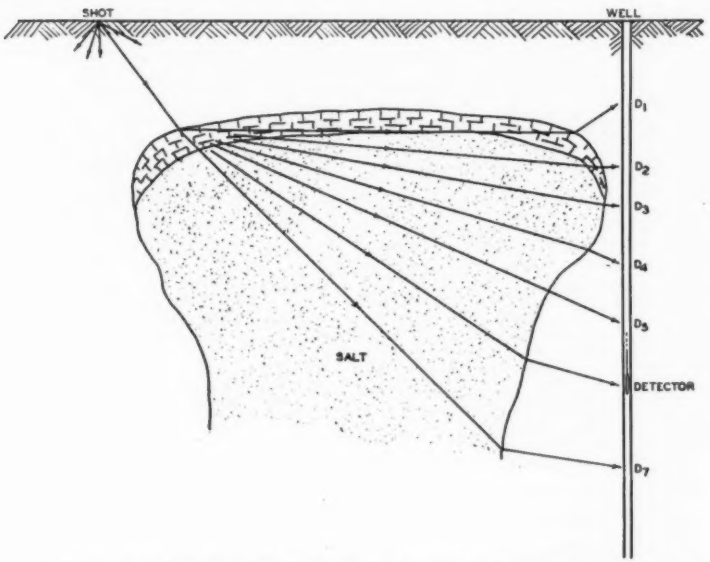


FIG. 3.—Sectional diagram showing use of well for profiling mushroomed flank of salt dome. Patent applied for.

If mushrooming is found to exist, the position of the flank of the dome, relative to the well, can be determined with considerable accuracy to a depth almost as great as that of the well.

Because of the very many deep or moderately deep wells around salt domes in the Gulf Coast region, many of which are, or could be made, available for work of this kind, this method may have extensive application. Any well open to the desired depth could be used and no injury to producing wells would result.

A further application of this method consists in the determination of the position of a fault plane at different depths, as shown in Figure 4. Here, for example, a well which was drilled too far back from the fault plane to obtain oil is used in determining the position of the fault plane for the purpose of making a second location.

GENERAL PROBLEM OF DETECTION OF MUSHROOMING

Use of the method discussed for profiling down the sides of salt domes determines not only the existence of mushrooming, should this exist, but

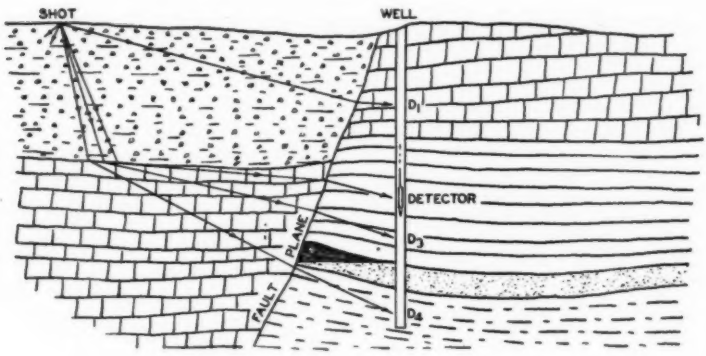


FIG. 4.—Diagram showing use of well for determining position of fault plane at different depths. Patent applied for.

also determines, with sufficient accuracy for all practical purposes, the extent of the mushroom condition. This can be done by the method previously outlined only in a zone immediately adjoining a well being used for the test. It is possible, however, by an extension of this method, to determine definitely the existence of mushrooming on a wide zone on the opposite side of the dome from that on which the well is located. The procedure is illustrated in Figure 5. Here the detector is placed at any suitable depth in the well and a shot is fired 4 or 5 miles away from the dome on the same side of the dome as the well. This shot point is designated as Shot Point 1 in Figure 5, its direction being indicated by the arrow. When the shot is several miles away from the dome, experience has shown that under these conditions the wave front, instead of being spherical, becomes somewhat ellipsoidal, the deeper parts of the wave front being far in advance of the shallower parts, as shown by the curved line representing such a wave front in Figure 5. Because of this bulging of the wave front with increasing depth, that part of the wave front which first reaches the detector at D_1 is far in advance of the position of the same wave front which reaches a series of detectors on the surface at D_2, D_3, D_4. If the detectors at all four of these positions be connected with a recorder, the amount of advance of the deeper parts of the wave front in excess of the surface part can be recorded accurately on a film.

Another shot is next placed at Shot Point 2 on the opposite side of the dome, and a detector, D_5, also is placed on the surface at a suitable point approximately symmetrical with respect to D_3 in relation to the

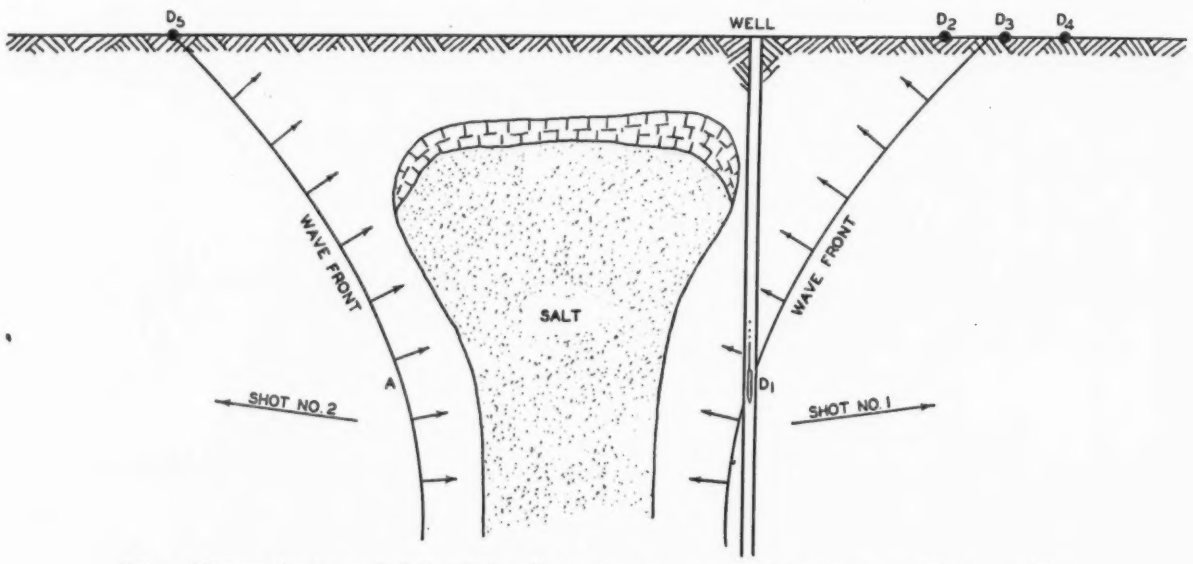


FIG. 5.—Diagram showing method of exploring side of dome opposite well for mushrooming. Patent applied for.

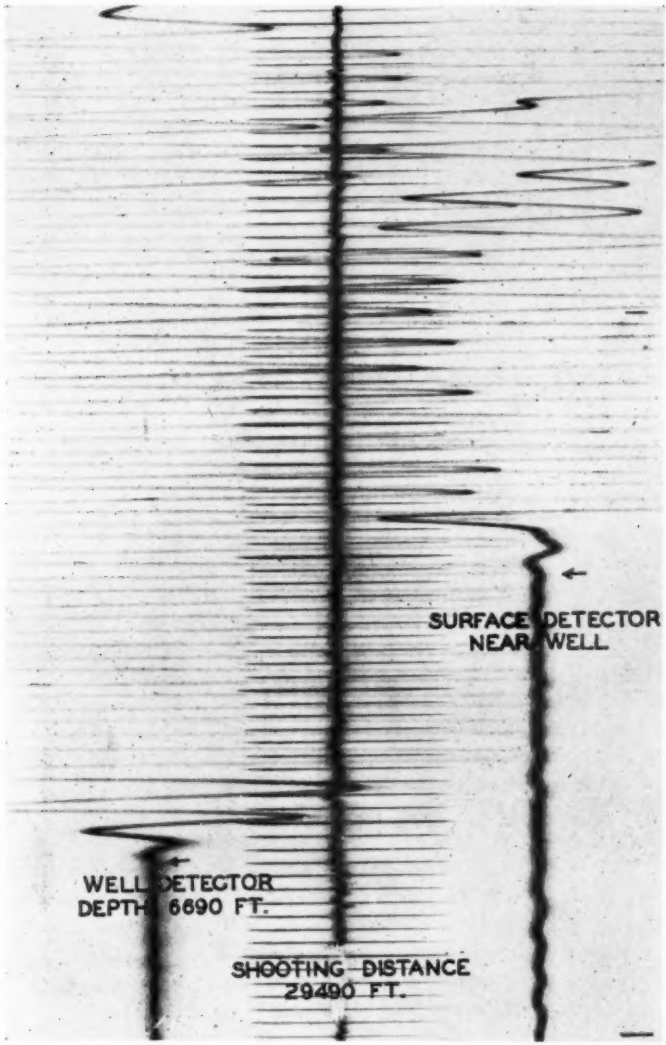
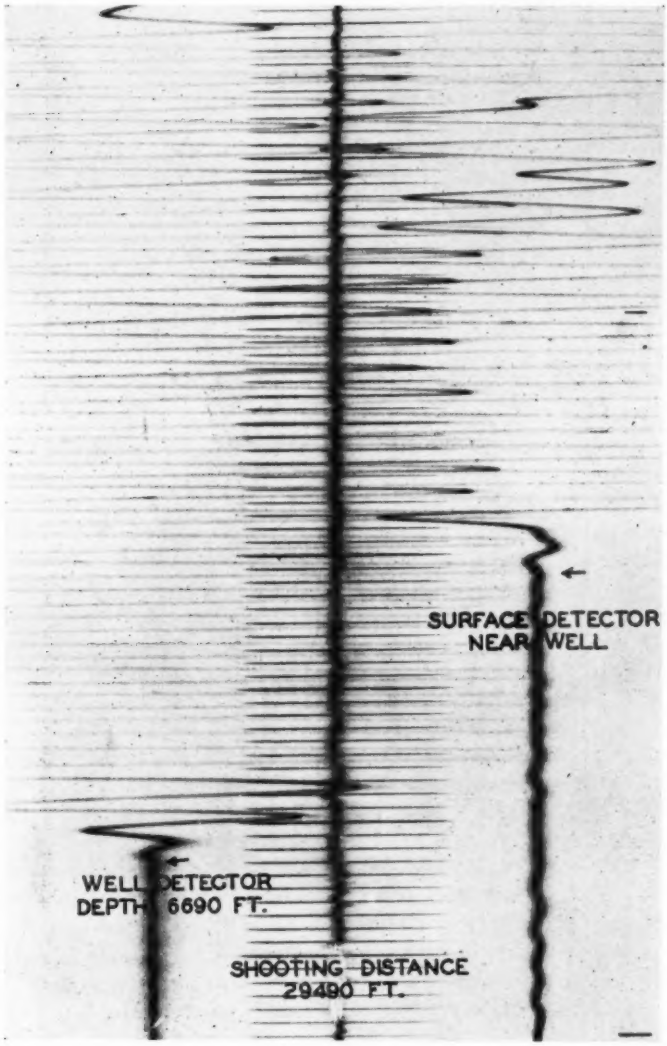


FIG. 6.—Typical record made with special seismic wave detector in well at depth of 6,690 feet (left trace). Notice greater velocity as compared with detector on surface near well (right trace). Shooting distance was 29,490 feet. Middle trace was not used.

dome. This shot is recorded on D_5 at the surface, also at D_1 in the well on the opposite side of the dome. By assuming the wave front to be the same from Shots 1 and 2, it is possible, after determining the time of arrival of the wave at D_5, to calculate the position of the deeper parts of the wave front; therefore, to determine definitely the position of a part, such as A, at a definite known time. From this, and the recorded time of the arrival of the same wave at D_1, the interval time between the positions A and D_1 is obtained. With the knowledge of this interval time and the velocity of sound in the shales and salt, and with the profile previously made of that side of the dome next to the well by the method shown in Figure 3, calculation can be made of the position of a point at a definite depth on the flank of the dome opposite the well.

Not only can this operation be completed on a line directly opposite the well, but similar lines can be shot, making an angle ranging from 30° to 45° on either side of the diametral line. Therefore, by the use of a single well, not only can the flank of the dome next to the well be accurately profiled, but it is possible to determine definitely the existence or nonexistence of mushrooming anywhere within a 90° angle on the opposite side of the dome.

It is obvious, therefore, that with two, or at the most, three wells, properly selected around any dome, the entire periphery of the dome can be explored thoroughly for mushroom conditions.



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ANALYSIS OF SOME TORSION-BALANCE RESULTS IN CALIFORNIA[1]

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ABSTRACT

The writer discusses torsion-balance results obtained in the Los Angeles basin. It is shown that here the distribution of gravity which is observed in the vicinity of an oil field is in no way connected with the inherent density of the beds. One phase of the mathematical theory of geophysics dealing with the gravity distribution set up by the folding of an otherwise uniformly dense bed is discussed, and it is shown that, in the region in question, the distribution of gravity is entirely the result of this folding. An approximate method of interpreting gravitational distribution in terms of subsurface structure is described.

Though the practical value of geophysics as a means of direct assistance in the solution of geological problems which confront many branches of oil exploration is far from being realized by many operators in California, this branch of geophysics has made great strides within the last few years, and is now equipped to give remarkably satisfactory subsurface information. The geological conditions in California are admittedly more complex than those of the coastal region of Texas and Louisiana, where geophysics was first used in the oil industry in the United States, but this complexity does not preclude the possibility of good results. After the difficulties have been overcome, more information may be deduced from geophysical studies in this region than in regions of simpler geology. The complexity of conditions in California, however, makes it necessary to leave the interpretation of the results to experts, in the same manner that micropaleontology is now left in the hands of a few men who really understand the work. When this is done the old record of geophysics will be erased and a new record established, which will encourage companies to spend their money on geophysical programs and subsequent leasing and drilling. There continue to exist erroneous ideas as to the nature of the properties of materials which are used in geophysical determinations, so that when the fundamental theory

[1]Presented before the Association at the San Antonio meeting, March 21, 1931. Manuscript received, February 12, 1931.

[2]Geologist and engineer, 438 South Maple Drive. Introduced by Paul B. Whitney.

of geophysics is examined by men who hold such erroneous ideas the result is confusion, and geophysical methods are hindered in getting the endorsement they merit.

It has generally been assumed that the distribution of gravity measured by the torsion balance depends on the configuration of denser or lighter rocks below the surface of the ground; in other words, it depends on the distribution of subterranean mass caused by the inherent density of the contorted beds, and as no inherent density differences are detectable within moderate depths in many places in California, this has been taken as *prima facie* evidence that the torsion balance was not adaptable to California conditions. When it was shown that all California oil fields do affect the distribution of gravity in their vicinity, the effect was attributed to slight inherent density changes, and the method of determining densities from core samples was questioned. Simple reasoning will show that the distribution of gravity in many oil fields in California has little if anything to do with the inherent density of the beds below the surface.

Figure 1 represents a cross section of an oil field in the Los Angeles basin. AA' is the observed gradient profile curve. The maximum ordinates, b and b', are 1,600 feet apart. BB' is the calculated gradient profile curve where a heavier bed of the same cross section just reaches the level surface of the ground at the crest of the fold, the ordinates of the profile curve being proportional to the difference in density of the heavier bed and the surface fill. This profile curve does not reach its maxima within the limits of the sketch. If this heavier bed had occupied a lower position in the series, or a higher position, and had been subsequently eroded to a level surface, the maxima on the profile curve would be still farther apart. Therefore, as the first case considered does not produce a distribution of gravity comparable with that observed in the field, no heavier bed in any position, nor any combination of lighter or heavier beds, nor increasingly lighter or heavier beds, can produce results in any way comparable with those observed. Hence it is proved that the observed distribution of density represented by the profile curve AA' does not depend on the inherent density change of the subsurface formations. Also, as all the oil fields in the Los Angeles basin cause a similar distribution of gravity, the proof may be extended to include them.

It seems probable that the causes which underlie the distribution of gravity over many structures in California must generally be sought in the compaction and rarefaction of the beds caused by folding. The forces of earth movement which give rise to structures generally remain

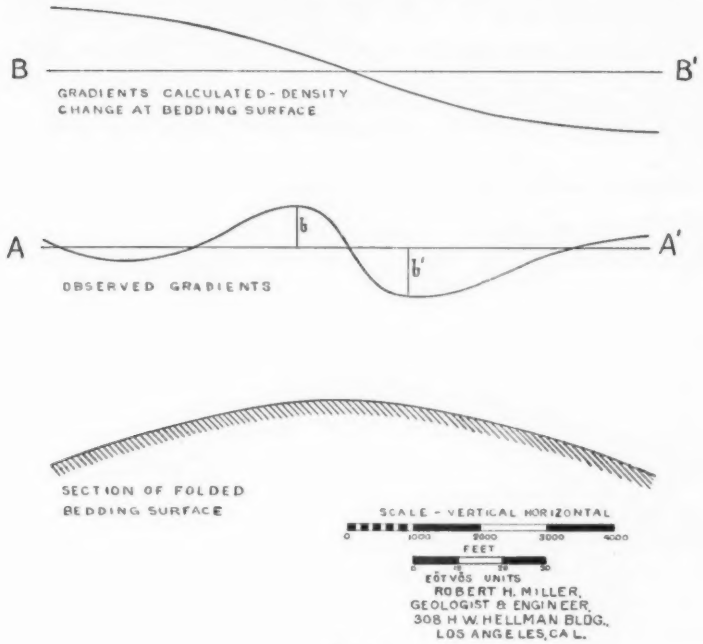

FIG. 1

active through a long period of time, and deposition and erosion occur contemporaneously in many places so that the formations at depth may be more folded than those at the surface. The effects of distance, however, more than offset the greater degree of folding that may occur at depth, so that only the folding of the surface formations has an appreciable effect on the distribution of gravity at the surface. When a whole series of formations is folded, the series may be divided into members that react to folding in the manner of rigid bodies and those that flow plastically or slip on cleavage planes; otherwise the strain in the materials would exceed all possible limits. It is not necessary to assume that sand beds exhibit the properties of rigid bodies and that under linear compression shales flow plastically, but it is a fact that surface sand formations, within 1,000 or 2,000 feet of the surface, when folded, assume a form that only rigid bodies would acquire under the circumstances. If allowances are made for the effects of friction, this form may

be expressed as a sine function. It will be shown that the distribution of gravity observed throughout many California oil fields is mainly the result of the folding of the surface formations which behave like a rigid surface crust.

AB (Fig. 2) represents a vertical section of a sand formation through one of the Los Angeles basin oil fields drawn to scale. Below this sand formation are blue shales. The sine function assumed by this bed may be expressed by

$$y = 1{,}000\left[1 - \cos\frac{x\pi}{9{,}000}\right]$$

where x and y represent, respectively, distance and height in feet from the origin O, of points on the lower surface of the bed. The points a and b are points of inflection at which there is no bending. Between a and b the arch is convex upward so that the part near the upper surface is extended, and the part near the lower surface is compressed. Between A and a, B and b, the arch is convex downward and the reverse is true. There is, therefore, a part of the bed between the upper and the lower surface which is neither extended nor compressed. This part of the bed is named the neutral surface, and its vertical section is the neutral axis. One of the consequences of bending is that at any point in a normal section the strain is proportional to the distance of that point from the neutral surface. As the change of density is equal to the strain, the terms may be used synonymously. If compression is considered as a positive density change and rarefaction as a negative density change, and if points above the neutral surface are considered positive and points below negative, the distance of a point from the neutral surface in a normal section, where the density change is δ, is given by a, where

$$a = \frac{\rho\delta}{1 + \delta}$$

ρ being the radius of curvature of the neutral axis at that section, being positive where the axis is concave upward and negative where the axis is concave downward. As the radius of curvature of a sine curve passes from a minimum at the points A, B, and C, to infinity at the points of inflection a and b, there is a deficiency of mass concentrated above the neutral surface at C, and below the neutral surface at A and B, and an excess of mass below the neutral surface at C and above the neutral

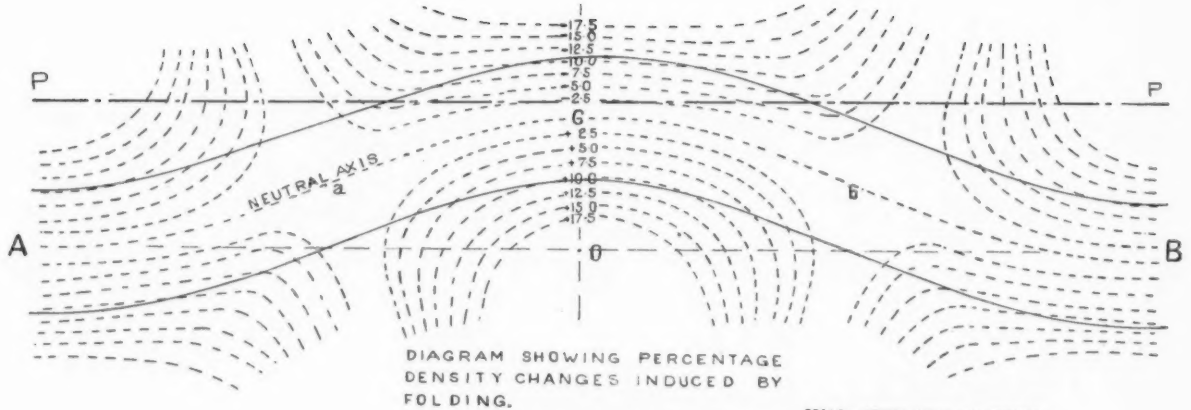
-17.5
-15.0
-12.5
-10.0
-7.5
-5.0
-2.5
P
P
G
+2.5
+5.0
+7.5
+10.0
+12.5
+15.0
+17.5
NEUTRAL AXIS
a
A
B
0
6
DIAGRAM SHOWING PERCENTAGE DENSITY CHANGES INDUCED BY FOLDING.
SCALE - HORIZONTAL = VERTICAL
0
1600
2000
3200
4000
FEET
ROBERT H. MILLER,
GEOLOGIST & ENGINEER,
308 H.W.HELLMAN BLDG.
LOS ANGELES, CAL.

FIG. 2

surface at *A* and *B*. The dashed lines represent surfaces of equal density, the figures referring to the percentage changes. It is thus evident that the mass within the bed is redistributed into six zones, occurring in pairs. The zones of each pair are of opposite nature and in the same vertical line. It is evident that the distribution of gravity at the surface caused by these zones depends on their magnitude and position relative to one another, which is a direct function of the fold, and their position as a group relative to the surface of the ground, which is a function of subsequent erosion, deposition, or earth movement. On the assumption that the normal density of the sand bed in Figure 2 is 1.8, and that subsequent to folding it has been buried to its crest under material of the same density, it is seen that the distribution of gravity would be represented by the calculated gradient profile curve *BB'* (Fig. 3). If erosion then took place to the plane *PP* (Fig. 2), the position of the base of the sand formation now coinciding with the blue shale contact of this particular field, the calculated distribution of gravity would be represented by the gradient profile curve *CC* (Fig. 3). The close similarity of this curve and the observed gradient profile curve in this field (curve *AA*, Fig. 3) is sufficient proof that the compaction and rarefaction of the surface formations resulting from folding is the direct cause of the observed distribution of gravity.

The practical value of this theory as a means of interpreting torsion-balance results in terms of subsurface structure can be illustrated best by considering an actual example. Curve *HK* (Fig. 4) is the actual gradient profile bed across an area in the Los Angeles basin drawn to the scales shown. This curve is complex and is obviously the composite of several simpler curves. On analysis the curve is found to be composed of three simpler curves, *LM*, *NQ*, and *SV;* that is to say, the ordinate of any point on curve *HK* is the algebraic sum of the ordinates of the corresponding point on curves *LM*, *NQ*, and *SV*. It is evident from what has been said before that curve *LM* represents the distribution of gravity set up by the zone of compression below the crest of an anticline, and curve *NQ* represents the distribution set up by the remnant of a zone of extension above the crest of the anticline. Curve *SV* represents the distribution of gravity set up by the zones on the flank of the anticline, the upper zone of compression masking the lower zone of extension. As there is no disturbance on the other side of the anticline corresponding with *SV*, there is clearly a fault on that side against which the beds were folded. Referring to Figure 2, it is seen that, in the zone of compression at the axis of the anticline, the surfaces

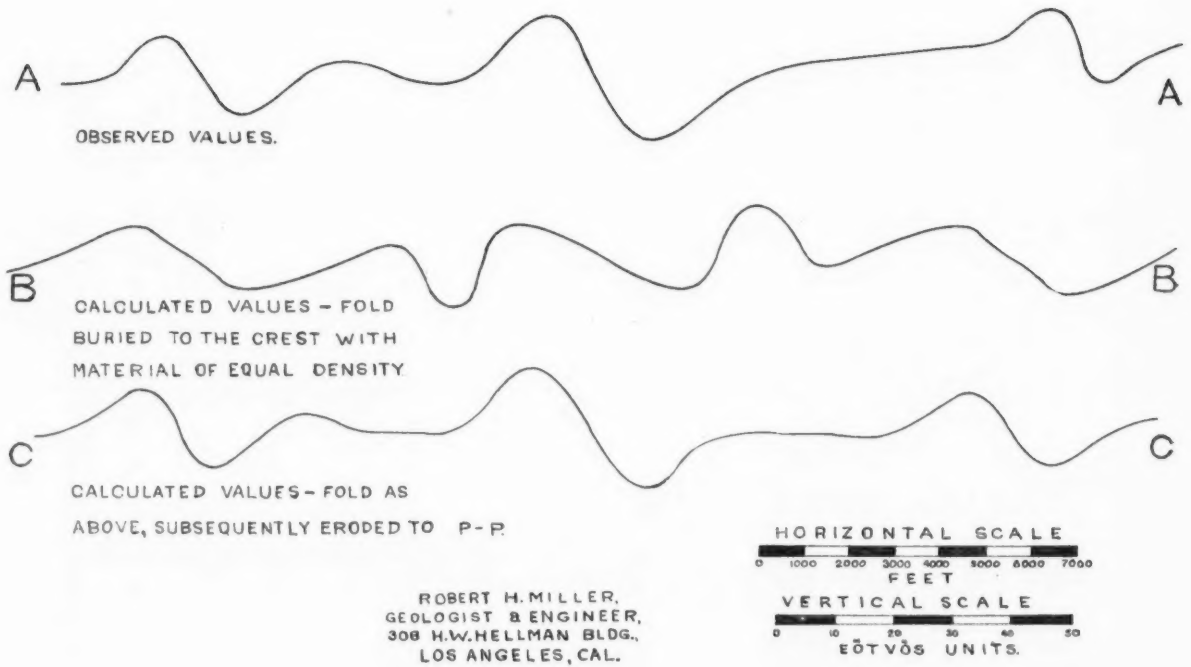
A
A
OBSERVED VALUES.
B
B
CALCULATED VALUES - FOLD
BURIED TO THE CREST WITH
MATERIAL OF EQUAL DENSITY
C
C
CALCULATED VALUES - FOLD AS
ABOVE, SUBSEQUENTLY ERODED TO P-P
HORIZONTAL SCALE
0 1000 2000 3000 4000 5000 6000 7000
FEET
VERTICAL SCALE
0 10 20 30 40 50
EÖTVÖS UNITS.
ROBERT H. MILLER,
GEOLOGIST & ENGINEER,
308 H.W. HELLMAN BLDG.,
LOS ANGELES, CAL.

FIG. 3

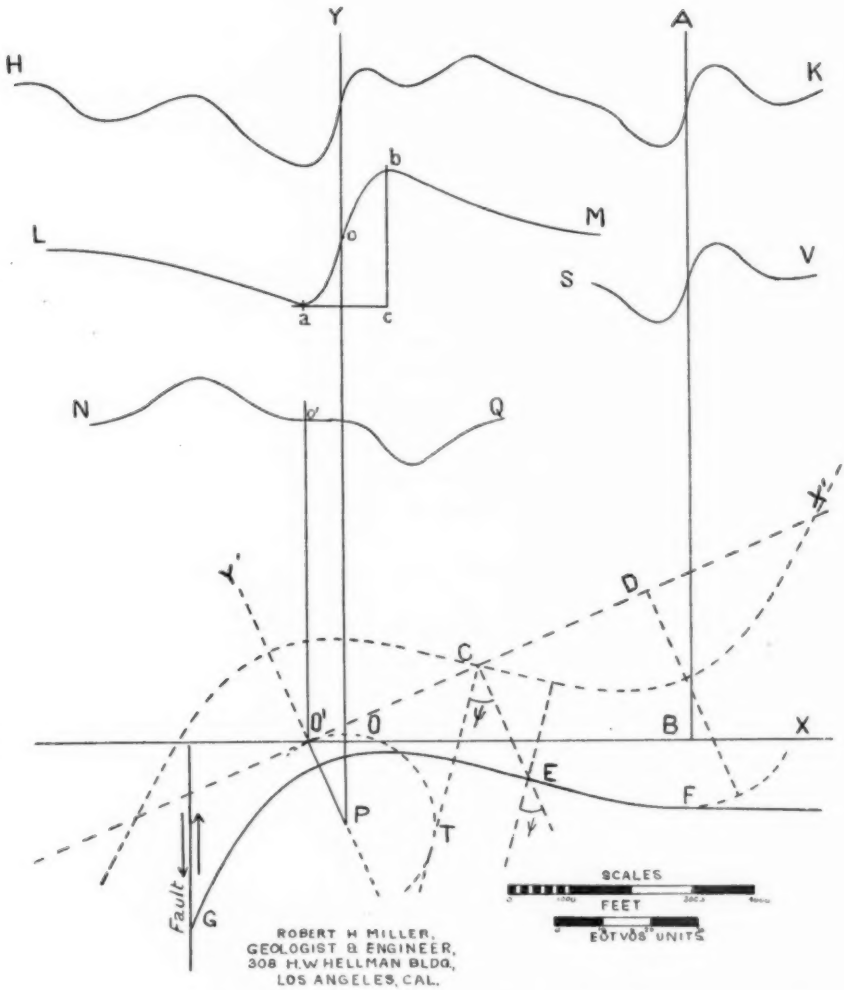

FIG. 4.—Graphical construction for the interpretation of results. For explanation see text.

of equal density present approximately concentric cylindrical surfaces in the immediate vicinity of the axis and that the center of curvature of these parts of these surfaces is approximately equidistant from the horizontal line tangent to the neutral axis and to the normals through the points of inflection *a* and *b*. Therefore, close to the axis, the distribution of gravity caused by the disturbing mass in this zone is approximately the same as if the mass were concentrated at this point, namely, the center of the circle touching the normals through the points of inflection and the ground surface, to approximate still further. Thus, in curve *LM* (Fig. 4) the two maxima are the distance *ac* apart, so that if *OX* represents the surface of the ground, the point would be located at *P*, a distance *ac* below the surface. The point of symmetry of curve *NQ*, representing the distribution of gravity caused by the remnant of a zone of extension at the axis of the anticline, is offset toward the left from that of curve *LM*, indicating that the beds have been dragged down by the fault at the time the anticline was formed, and that the sine curve which is the figure of the anticline must be referred to the new axes *X'O'Y'* instead of the horizontal and vertical axes *XOY*. The construction is evident from the figure. On account of the rotation of the axes, the period of the sine curve representing the anticline is slightly greater than *OB*, because at the point *F*, vertically below the center of the zones represented by the profile curve *SV*, the beds are horizontal, and not parallel with the new axis *O'X'*. The period of the sine curve is estimated to be *O'D*, and *C* is the point of inflection of the sine curve referred to the axes *X'O'Y'* (shown by the dashed line). The tangent *CT* to the circle *O'T*, with *P* as center, gives the inclination ψ of the normal through the point of inflection. Now the equation of this sine curve is

$$y' = a\left[1 - \cos\frac{x'\,\pi}{O'D}\right]$$

where *a* is a constant representing the half-amplitude of the sine curve and *O'D* is the half-period, equal to 6,000 feet, and

$$\tan\psi = \frac{dy'}{dx'} = \frac{a\pi}{6{,}000} \qquad (1)$$

By measurement the angle *TCE* (ψ) is 39.5° and the tangent is 0.83, and x equals *O'C* and is 3,000 feet. Substituting these values in equation (1), *a* is found to be 1,600 feet, approximately. The section of the anti-

cline, therefore, represented by the profile curve *HK*, is a sine curve having a period equal to *O'D* and a half-amplitude of 1,600 feet. This curve is represented by curve *GEF* in the figure. As the point *G* has been dragged below its original level *F*, it is evident that the fault is downthrown on the left. As the earth movements which caused the anticline evidently caused motion of the beds from left to right, friction and inertia must have caused the horizontal dimensions to be foreshortened to an extent varying inversely with the distance from the fault, so that the fault is nearer the axis of the anticline than is indicated by this theoretical analysis, and the left limb of the fold is somewhat steeper.

Though this discussion has been devoted solely to the distribution of gravity in the Los Angeles basin, where the density conditions are exceptional, an accurate interpretation can be made of the data acquired from measuring any of the other properties of materials which are utilized in geophysics in any region, provided that the data which have been obtained are complete.

DISCUSSION

FRANK A. MOSS, Los Angeles, California (written discussion received, March 12, 1931): The author of the preceding paper offers an interesting explanation for gradient profiles in which the points of maximum gradient are too close together to be caused by density differences in beds extending across a fold. In a loosely consolidated bed of sand, folding reasonably could be expected to cause an increase of density as postulated, but it is questionable whether there would be a decrease in density due to tension. However, there still would be gravity "highs" over the crest of the fold and over the flanking synclines.

Other possibilities to be considered in the example given are (1) that the gravity "highs" on either side of the fold could be caused by heavy beds truncated and covered by alluvium and (2) that a combination of lenses of heavy and light materials might distort the effect of inherent changes in density sufficiently to produce the results observed.

These theoretical considerations do not apply to folds in the western side of the San Joaquin Valley, where the beds involved in the folding are fairly well indurated and would be sheared rather than appreciably compressed. Observed variations in gravity can be related satisfactorily to measurable changes in density of the underlying materials.

DONALD C. BARTON, Houston, Texas (written discussion): Geologically, it seems to me that we must examine more closely the reasoning leading to the assumptions that a soft, poorly consolidated California sediment will act as if it were a rigid body. Without more definite corroboratory data, I would be unwilling to postulate the compression-rarefaction assumed by Mr. Miller.

Geophysically, I can not reach Mr. Miller's conclusions. Mathematically, it commonly is possible to obtain a considerable series of tentative structural

profiles all of which produce gradient profiles which check given observed gradient profiles within the limits of the probable error. A close fit of a calculated to an observed gradient profile is not necessarily evidence that the trial structure section is correct. In the Belle Isle survey, I found that geologically improbable assumptions and a trial structure section now proved to be incorrect gave a very much better fit of calculated to observed gradient profiles than assumptions and structure sections 75 per cent of which have been confirmed by subsequent drilling.

A year ago I had the pleasure of studying a rather extensive torsion-balance survey which disclosed the structure of Figure 3 with fair detail and which also gave a fair picture of the gravitational situation of the surrounding area. This study of Mr. Miller's in a preliminary form also was seen by me. My study of that torsion-balance survey seemed to show that the gravitational picture over the particular structure could not be interpreted intelligently if it and the structure were studied separately from the anomaly of the major structural features of that part of the basin. Some of the smaller irregularities in that profile furthermore seemed to me referable to surficial irregularities in density.

Although I can not accept the conclusions expressed in this paper, studies of this type are necessary if we are to improve our technique of interpretation of torsion-balance surveys, and one of the problems which must be investigated is the effect of structural compaction.

SOURCE AND DATE OF ACCUMULATION OF OIL IN GRANITE RIDGE POOLS OF KANSAS AND OKLAHOMA[1]

JOHN L. RICH[2]
Ottawa, Kansas

ABSTRACT

All oil pools extending from El Dorado, Kansas, to Oklahoma City along the Nemaha granite ridge and the southern extension of that line of folding have important oil accumulations at an unconformity beneath the Pennsylvanian shales. This relation, together with evidence from later folds in the region, furnishes data from which the approximate date of oil migration and accumulation can be determined. Consideration of various possible sources for this oil indicate that it was not generated until long after the sediments were deposited, and that its source can not logically and consistently be sought in the rocks in the immediate vicinity of the pools. Generation of the oil by metamorphic agencies during the Appalachian revolution and its migration, in some regions through long distances, to its present reservoirs through porous carrier beds is a suggested hypothesis which seems to accord better with the data from the fields than do any of the hypotheses of local origin of the oil.

INTRODUCTION

Extending from Florence, Kansas, southward into central Oklahoma is a line of large and exceptionally prolific oil pools, including Florence, Peabody, Elbing, El Dorado, Augusta, Blackwell, South Blackwell, Tonkawa, Garber, Oklahoma City, and Cushing[3] (somewhat east of the line), all of which have similar geological structure and seem to have had nearly the same geological history. Because the major features of their

[1]Expanded from paper read before the Association at the San Francisco meeting, March 21, 1928. Manuscript received, May 5, 1931.

[2]Consulting geologist. Present address, department of geology, University of Cincinnati, Cincinnati, Ohio.

[3]For further details concerning these fields and their geologic history the following may be consulted.

C. R. Thomas, "Flank Production of the Nemaha Mountains (Granite Ridge), Kansas," *Structure of Typical American Oil Fields*, Vol. I (Amer. Assoc. Petrol. Geol., 1929), pp. 60-72.

John R. Reeves, "El Dorado Oil Field, Butler County, Kansas," *Structure of Typical American Oil Fields*, Vol. II (Amer. Assoc. Petrol. Geol., 1929), pp. 160-67.

A. E. Fath, "Geology of the Eldorado Oil and Gas Field, Butler County, Kansas," *State Geol. Survey of Kansas Bull. 7* (1921).

N. W. Bass, "The Geology of Cowley County, Kansas, with Special Reference to the Occurrence of Oil and Gas," *State Geol. Survey of Kansas Bull. 12* (1929).

Stuart K. Clark and James I. Daniels, "Relation Between Structure and Production in the Mervine, Ponca, Blackwell, and South Blackwell Oil Fields, Kay County,

geological structure were formed at the same time as the Nemaha granite ridge of Kansas and several of the pools are on that ridge or on the southward continuation of its axis, they are, for brevity, here referred to as the pools of the Granite ridge group.

Some features of these pools, particularly the occurrence of the oil mainly at the pre-Pennsylvanian unconformity, and the relation of the rocks which have been generally believed to have been the source of most of the oil in the region to that unconformity, provide means for dating approximately the period of oil accumulation and for testing some of the current theories of the source and migration of the oil in comparison with the field evidence as viewed in a broad way for the region as a whole.

GEOLOGIC HISTORY

A brief sketch of the major features of the region in which the Granite ridge oil pools occur will make clear their broader relations to each other, to the most probable sources of the oil, and to the principal structural disturbances of the district.[1]

The late Cambrian-early Ordovician Arbuckle limestones (known as "Siliceous lime" by drillers) were deposited on all those parts of Oklahoma and Kansas with which we are concerned. Deposition of the Arbuckle seems to have begun in southern Oklahoma where it is now

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Oklahoma," *Structure of Typical American Oil Fields*, Vol. I (Amer. Assoc. Petrol. Geol., 1929), pp. 158-75.

Glenn C. Clark, "Wilcox Sand Production, Tonkawa Field, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 9 (September, 1926), pp. 885-91.

Wesley G. Gish and Raymond M. Carr, "Garber Field, Garfield County, Oklahoma," *Structure of Typical American Oil Fields*, Vol. I (Amer. Assoc. Petrol. Geol., 1929), pp. 176-91.

T. E. Weirich, "Cushing Oil and Gas Field, Creek County, Oklahoma," *Structure of Typical American Oil Fields*, Vol. II (Amer. Assoc. Petrol. Geol., 1929), pp. 396-406.

Homer H. Charles, "Oklahoma City Oil Field, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 12 (December, 1930), pp. 1515-33.

"Oil and Gas in Oklahoma," *Oklahoma Geol. Survey Bull. 40*, Vol. 1 (1928), Vol. 2 (1930), Vol. 3 (1930), especially Luther H. White, "Subsurface Distribution and Correlation of the Pre-Chattanooga ('Wilcox' Sand) Series of Northeastern Oklahoma," Vol. 1 (*Bull. 40-B*), pp. 21-40; and G. C. Clark and C. L. Cooper, "Kay, Grant, Garfield, and Noble Counties," Vol. 2 (*Bull. 40-H*), pp. 67-104.

Hugh W. McClellan, "Subsurface Distribution of Pre-Mississippian Rocks of Kansas and Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 12 (December, 1930), pp. 1535-56.

Robert Roth, "Regional Extent of Marmaton and Cherokee Mid-Continent Pennsylvanian Formations," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 10 (October, 1930), pp. 1249-78.

[1]For his account the writer has drawn freely on material presented in papers already listed and especially on Luther H. White's "Subsurface Distribution and Correlation of the Pre-Chattanooga ('Wilcox' Sand) Series of Northeastern Oklahoma," *Oklahoma Geol. Survey Bull. 40-B* (June, 1926).

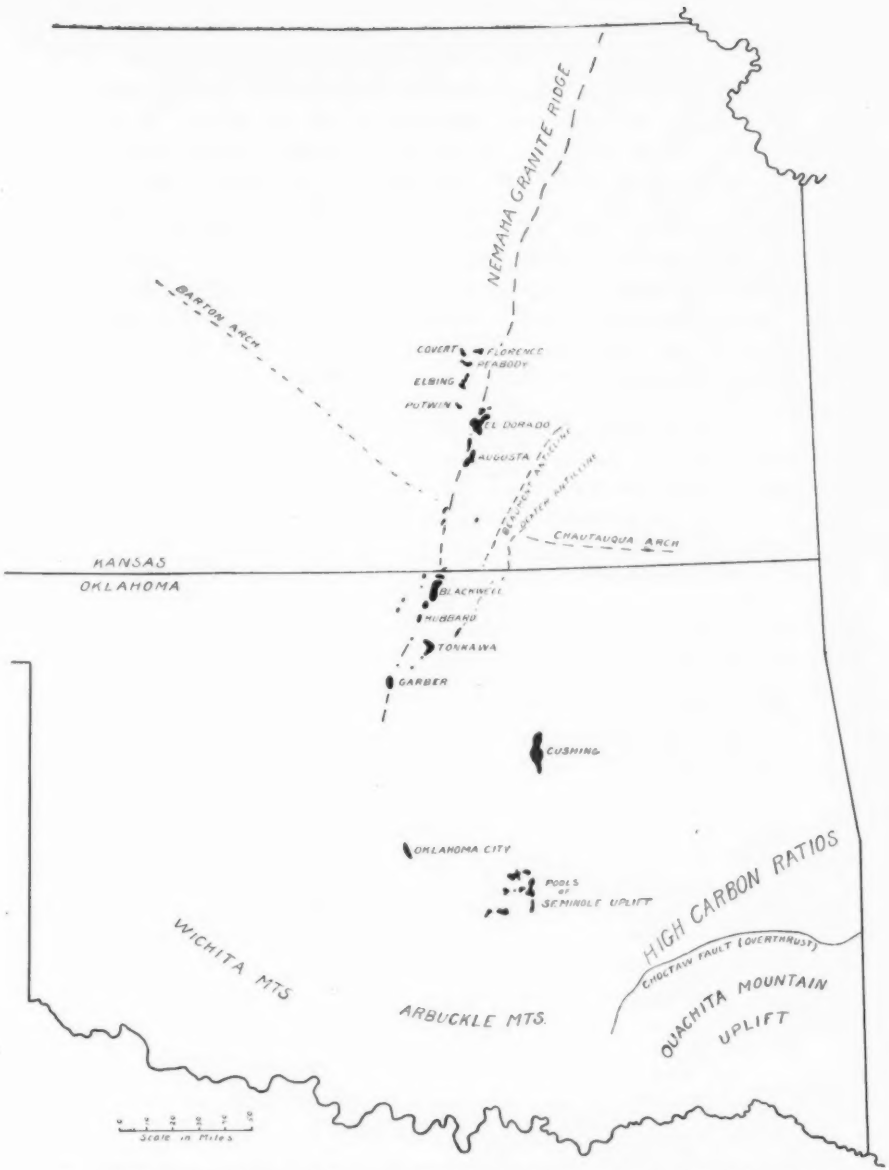


FIG. 1.—Key map of parts of Kansas and Oklahoma, showing location of oil pools and structural features under discussion. East of the pools here shown are many pools in both Oklahoma and Kansas which, for simplicity, have been omitted.

thickest and whence it seems to have spread northward and northwestward. Later, the region was uplifted and for a long time the Arbuckle limestone floored a low land, at least in the northern half of the area. Still later, near the close of the Ordovician, this land was submerged and the sediments of the Simpson formation, a series of shales, thin dolomites, and extensive sheet sandstones, were deposited. Its principal sheet sand, the "Wilcox," which seems to correspond with the St. Peter sandstone of adjacent states, is now the most prolific oil-producing sand in the district. The Simpson formation and its sands were thickest in southern Oklahoma and considerably thinner in northern Oklahoma and southern Kansas, but, so far as we know, they once covered all of the area under discussion.

Simpson deposition was followed by a period of slight emergence, after which the region again sank and the Viola limestone, approximately 50 feet thick, the Sylvan shale, of Upper Ordovician age, 75-125 feet thick, and the Hunton limestone, representing part of Siluro-Devonian time, were deposited, evidently throughout the whole region.

The deposition of the Hunton limestone was followed late in Devonian time by uplift, broad warping, and extensive peneplanation during which, on the Chautauqua arch in southeastern Kansas and the Barton arch in west-central Kansas,[1] all of the formations down to and including part of the Arbuckle limestone were removed by erosion. The peneplaned surface thus formed seems to have been extremely flat.

Early in Mississippian time this broad, flat plain was submerged and the dark, organic muds which formed the Chattanooga shale were deposited with remarkable uniformity throughout the whole region. The Chattanooga, notwithstanding its wide extent, is comparatively thin, ranging from only a few feet to slightly more than 200 feet, but having an average thickness between 20 and 50 feet in this area.

Deposition of the Chattanooga shale was followed conformably by that of the "Mississippi lime," which also is characterized by remarkable uniformity in large areas. Its average thickness was at least 350 feet. How much more it may have been and how great a thickness of later Mississippian rocks may once have been present and have been eroded we do not know.

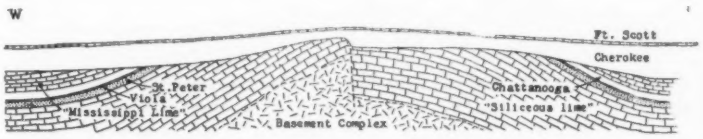
The deposition of the "Mississippi lime" was followed during the latter part of Mississippian or the early part of Pennsylvanian time by another uplift which seems to have been slight in amount and uniform

[1] John S. Barwick, "The Salina Basin of North-Central Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 2 (February, 1928), pp. 177-99.

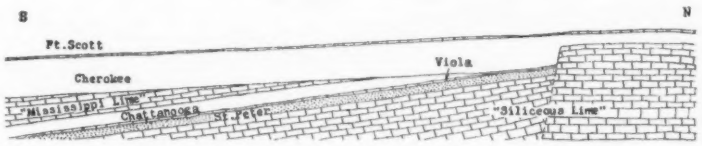
in large areas, for the Mississippian rocks were eroded at the top and slightly beveled, and a topography of low hills and valleys was developed on them in most of Kansas and the greater part of northern Oklahoma, but only here and there did erosion cut down entirely through the formation. The remaining lower part of the "Mississippi lime" has a remarkably uniform thickness ranging from 200 to 350 feet in large areas.

In contrast to the slight, uniform regional uplift of most of the area at this period, was the sharp linear folding and faulting which produced the Granite ridge (Nemaha Mountains) of Kansas and the related structures farther south and southeast. Whether this sharper local folding and faulting occurred at the beginning of the late Mississippian uplift, during it, or near its close, is uncertain, but the last seems most probable.

Along these sharper folds and faults the "Mississippi lime" and older formations were brought up above peneplain level and stripped well down into the Arbuckle limestone on the Oklahoma structures and down to and into the pre-Cambrian on the Granite ridge north from the vicinity of El Dorado, Kansas (Figs. 2 and 3).



Ideal west-east cross section of El Dorado anticline from Sec. 7, T. 26 S., R. 4 E., to Sec. 12, T. 26 S., R. 5 E. Length, 12 miles; height, 1,200 feet.



Ideal south-north cross section of southern part of El Dorado anticline from Sec. 31 to Sec. 8, T. 26 S., R. 5 E. Length, 5 miles; height, 500 feet.

FIG. 2.—El Dorado pool, Kansas. Cross sections of typical Granite ridge structure of faulted type showing geologic relationships at pre-Pennsylvanian unconformity. By John R. Reeves, "El Dorado Oil Field, Butler County, Kansas," *Structure of Typical American Oil Fields*, Vol. II (Amer. Assoc. Petrol. Geol., 1929), p. 161.

In the early part of the Pennsylvanian period we may picture northeastern and north-central Oklahoma and the eastern two-thirds of Kansas as a peneplaned limestone land of slight relief, close to

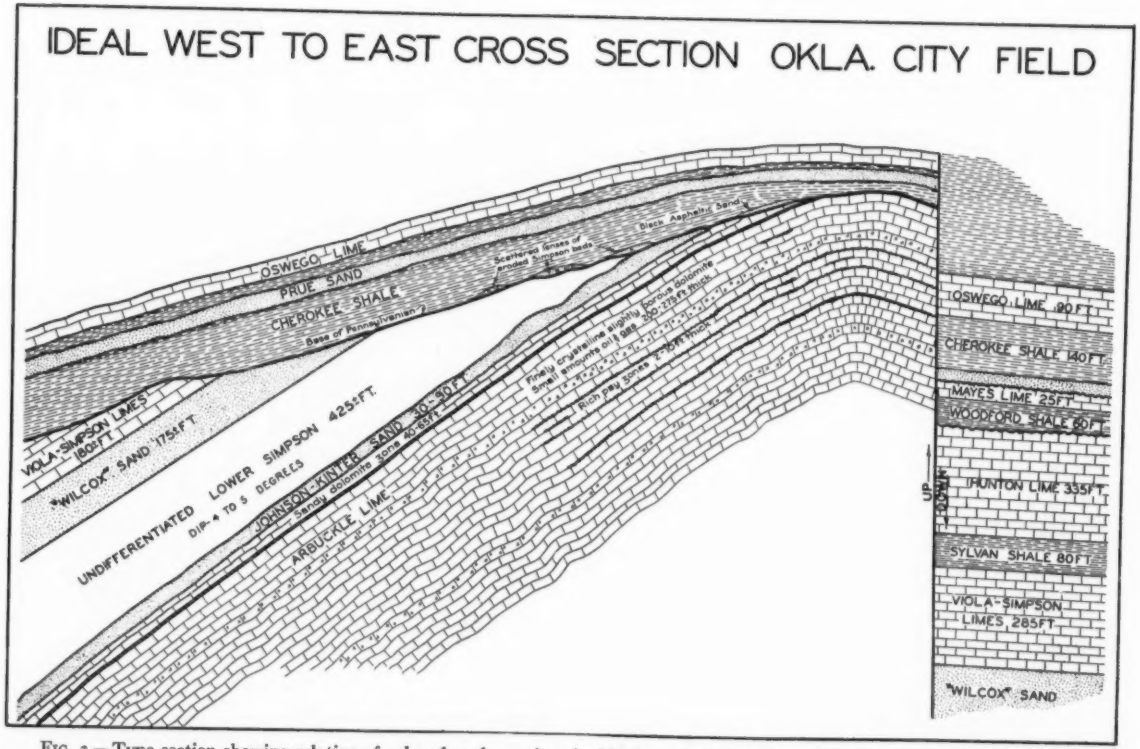


FIG. 3.—Type section showing relation of subsurface formations in Oklahoma City field. Length of section, approximately 3 miles. By Homer H. Charles, "Oklahoma City Oil Field, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 12 (December, 1930), p. 1522.

sea-level. The Granite ridge and its related structures on the south were presumably marked by low, rolling hills, slightly above the general level.

During Cherokee time, early in the Pennsylvanian, a shallow north-south basin began to settle below sea-level in eastern Oklahoma and in Kansas east of the Granite ridge. Before the end of Cherokee time the submergence spread to all of Oklahoma with which we are here concerned and to southern and southwestern Kansas, but the Granite ridge north of El Dorado remained above water and the area west of it, at least along the saddle extending westward to the Barton arch, seems not to have been covered until very late Cherokee or the beginning of Marmaton time.

The blue, gray, and black shales which compose most of the Cherokee formation have generally been considered as one of the most probable sources of oil in this district. Their thickness ranges downward from approximately 900 feet in the deeper parts of the basin. A common thickness in much of the basin is 300-350 feet, but in the area with which we are particularly concerned the thickness generally reported is considerably less.

Following the local submergence which formed the Cherokee basin east of the Granite ridge, came a more widespread subsidence, so that by Marmaton time the Pennsylvanian sea covered the southern part of the Granite ridge and the country west of it except, perhaps, the highest parts of the Barton arch. Submergence and deposition then continued through the remainder of the Pennsylvanian and much or all of the Permian until sediments ranging in thickness from 3,000 to 10,000 feet had been deposited over the buried Mississippian folds.

At intervals during the Pennsylvanian and Permian came the structural disturbances of the Appalachian revolution, during which the Ouachita Mountains were severely folded and faulted and their rocks subjected to sufficient metamorphism to raise their carbon ratios beyond the limits of oil retention (more than 80).

At some undetermined time subsequent to the deposition of the Pennsylvanian rocks there was a second period of folding along axes approximately parallel with the Granite ridge, which formed long, moderately sharp anticlines such as the Beaumont and Dexter anticlines which lie 20-30 miles east of the Granite ridge. These folds differ from those of the Granite ridge group in that the "Mississippi lime" and the Pennsylvanian formations maintain approximately their full thickness on the folds. They differ further in having caused only minor accumulations of oil and gas, in contrast to the rich accumulations on the earlier folds of the Granite ridge group.

Besides the distinct anticlinal folds, there are also many structures whose form suggests deep-seated faulting, which do not affect the thickness of the rock sections on them, and which obviously were formed after deposition had been completed. Their age is unknown. It may be as late as Cretaceous or Tertiary.

Another important event whose date does not seem to be definitely known is the westward tilting of the Oklahoma-Kansas area (except, perhaps, the western third of those states) to an amount ranging from 20 to 80 feet per mile. This tilting may have occurred mainly at one period or it may have continued gradually ever since erosion began to strip off the rocks piled up during the Appalachian revolution.

Such, in brief, is the geological history of the region in which the Granite ridge group of oil pools is found.

GRANITE RIDGE OIL POOLS

North of El Dorado, Kansas, the Mississippian and Ordovician rocks have been mostly stripped from the crest of the Granite ridge, but between El Dorado and Oklahoma City almost every fold of the Granite ridge type has been proved to hold a rich oil pool.

The greatest, and presumably the primary, accumulations of oil in most of these pools occur in the upturned and beveled edges of the Ordovician and Mississippian rocks at the unconformity where they are overlain by the Pennsylvanian shales (Figs. 2 and 3). Other large accumulations of both oil and gas occur higher in the section on the same folds in sands of both Pennsylvanian and Permian age and they extend within a few hundred feet of the surface. These higher accumulations have many of the characteristics of secondary origin and of having been formed by oil working its way upward through fissures from the deeper pools.

Among the evidences of such secondary origin of the oil in the higher sands are: (1) similarity in composition between the oil in the higher sands and that in the main pools below; (2) evidence of considerable fissuring on the structures; (3) general absence of oil and gas in the lenticular sands of the higher formations away from the producing structures.

In the beveled beds beneath the Pennsylvanian shales the oil seems to be found in whatever members of the Ordovician and Mississippian section happen to furnish the best reservoirs, and this seems to depend in large measure on the amount of stripping to which the fold was subjected in pre-Pennsylvanian time. On folds where the Arbuckle limestone was laid bare, as at El Dorado, Garber, and Oklahoma City, the

oil has accumulated in the Arbuckle, in the ring of "Wilcox" and other Simpson sands surrounding it, and here and there in the beveled edge of the "Mississippi lime." In other pools, as at Tonkawa, the "Wilcox" sand, which is covered by the Viola limestone in most of the field, is the principal producing horizon. At Oklahoma City richly productive streaks have been found in the Arbuckle limestone as deep as 500 feet below its top.

The Churchill (Sec. 24, 25, 36, T. 31 S., R. 2 E.) and Oxford (Sec. 12, 14, 22, 23, T. 32 S., R. 2 E.) pools of Kansas show an interesting variation from the general rule in that the principal accumulation is in sands near the middle of the Pennsylvanian section. The greater part of the oil produced has come from the Stalnaker sand at the contact of the Lansing and Douglas groups, but in the Oxford pool oil in commercial quantities has been found also in several wells in sands 500 feet higher in the section, and in a few wells several hundred feet still higher.[1]

Tests of the deeper Mississippian and Ordovician formations, which produce most of the oil in the other Granite ridge pools, have shown those formations to contain only water.

Such an abnormal distribution of the oil in these structures is not readily to be explained by differences in the source rocks adjacent to the reservoir sands. It suggests strongly that those particular structures have been fissured so extensively that all of the oil has escaped upward from the deeper formations and has been trapped by the sands higher in the section.

COMPARISON WITH LATER FOLDS

In the preceding section mention has been made of two periods of folding, one in late Mississippian-early Pennsylvanian during which the folds and faults of the Granite ridge type were formed, and another at some undetermined post-Pennsylvanian time when the Beaumont anticline and related folds were formed. The post-Pennsylvanian disturbances of the fault type may have occurred at the same time, but it seems more probable that they were later.

The folds of the Granite ridge group (south of El Dorado) have, almost without exception, become the centers of rich oil accumulation. Those of the later, post-Pennsylvanian generation, have proven disappointing for oil, particularly in the deeper sands, though they have

[1] L. W. Kesler, "Oil and Gas Resources of Kansas in 1927," *State Geol. Survey of Kansas Min. Resources Cir. 1* (June, 1928). The same description is also printed in *Petroleum Development and Technology in 1927* (Amer. Inst. Min. Met. Eng., 1928), pp. 589-90.

caused minor accumulations of oil in the top of the "Mississippi lime" and of gas in some of the higher beds.

The difference in the oil content of the folds of the two generations is believed to furnish a clue to the origin and date of generation of the oil in this region.

The essential differences between the conditions on the two folds are: (1) on the Granite ridge folds the rocks beneath the Pennsylvanian were uplifted and beveled before the Pennsylvanian was deposited; on the later folds the Mississippian formations are thinned only slightly and the Pennsylvanian has its full thickness; (2) the Granite ridge folds were present at the time of the Appalachian revolution and at the time of the first loading of the Chattanooga and Cherokee shales by the weight of the Pennsylvanian and Permian rocks; the later folds seemingly were not; (3) on the Granite ridge folds the present reservoir rocks are in contact with the Cherokee shales in some of the pools, but not in all, and might have been reached by oil from the Chattanooga on the flanks of the structures ascending along the unconformity. On the later folds the Cherokee is in contact only with the top of the "Mississippi lime," and the Chattanooga is in contact with various members of the Ordovician section, differing from place to place because of the pre-Chattanooga beveling.

DATE OF OIL ACCUMULATION

Having sketched the geological history of the region and the distribution of the oil pools with respect to the folds of the earlier and later generations, we are ready to analyze the question of the date of the oil accumulation and from that to work toward a solution of the problem of its source.

As the major oil accumulations are found at the unconformity below the Pennsylvanian rocks or in them, it is obvious that the oil accumulation was a post-Pennsylvanian event. Whether the oil accumulation began as soon as the older rocks were buried and continued while the remaining Pennsylvanian sediments were being deposited is not yet known. The fact that the higher parts of several of the structures such as Oklahoma City, El Dorado, Elbing, Peabody, and Florence were not buried until latest Cherokee or early Marmaton time fixes the earliest possible date for the beginning of accumulation in those pools.

It seems that the oil migration must have been almost completed before the formation of the later folds, such as the Beaumont anticline; otherwise those folds should have trapped their share of the migrating oil.

We can thus place the date of the accumulation of the oil in the Granite ridge pools between the beginning of Marmaton time and the time of the formation of the later folds, which, unfortunately, we do not know definitely.

It is thought to be significant that the time of accumulation as thus fixed includes the time of the Appalachian revolution of southeastern Oklahoma and adjacent states.

SOURCE OF OIL

Having fixed, approximately at least, the date of accumulation of the oil, we have next to inquire as to its probable source.

Three possibilities are to be considered, the first two being local and the third a distant source: (1) the Chattanooga shale and older rocks; (2) the Cherokee and Marmaton shales; and (3) a source in any of the foregoing or in other rocks, but far removed from the present fields—specifically, oil generated in southern and southeastern Oklahoma by the regional metamorphism induced by the Appalachian revolution.

Gish and Carr, in describing the Garber pool,[1] give good reasons for the belief that most of the oil in the fields geologically associated with the Ordovician sediments came from Ordovician rocks. They state that a survey of such fields

> reveals that those pools which do not have Viola limestone as a cap rock for the "Wilcox" sand are characterized by oil and gas production in large amounts in the overlying Pennsylvanian and Permian rocks, while in a typical "Wilcox" sand pool with its Viola limestone capping the producing sand, the prolific production is in the "Wilcox" sand and shallower production is the exception rather than the general rule.

Gish and Carr's argument, however, applies to the Ordovician as the channel of migration, but not necessarily as the ultimate source of the oil.

Other writers have referred to the Chattanooga as the probable source rock, and still others to the Cherokee or both Chattanooga and Cherokee.

CHATTANOOGA OR EARLIER ROCKS AS SOURCE OF OIL

We may grant at the outset that the Chattanooga, and probably also the Ordovician rocks below, are sufficiently rich in organic material to have furnished all of the oil required, but if the Chattanooga or earlier

[1] Wesley G. Gish and Raymond M. Carr, "Garber Field, Garfield County, Oklahoma," *Structure of Typical American Oil Fields*, Vol. I (Amer. Assoc. Petrol. Geol., 1929), pp. 176-91.

rocks were the source of the oil in the Granite ridge pools, we must explain the following sequence of events.

It has already been shown that the oil did not migrate to its present reservoirs until after Pennsylvanian deposition had begun. If the source was Ordovician, this means that the oil must have lain dormant in the sediments during the so-called biochemical stage shortly after their deposition; during the compaction which resulted from the deposition of the later Ordovician and Siluro-Devonian sediments; during the late Devonian period of uplift and widespread peneplanation; during Mississippian depression and sedimentation; during late Mississippian uplift and peneplanation; during the period of greatest folding of the region, namely, that which produced the Granite ridge structures; and during the beginning of Pennsylvanian sedimentation. Then, for some reason —and rather suddenly— the oil seems to have been generated and to have migrated to its present reservoirs during a period not marked by more than slight structural disturbance in the vicinity of the oil reservoirs, and the migration seems to have been substantially completed before the beginning of the later period of folding.[1]

If the Chattanooga were the source, the history would have been the same with the omission of the pre-Chattanooga stages.

Such a history seems entirely unreasonable in view of our knowledge about oil origin and migration. It seems to exclude the Chattanooga and older rocks as the source of the oil in all theories of local origin; of origin as oil deposited with the sediments or as oil generated by biochemical agencies soon after deposition; and of origin and migration related to the initial compaction of the sediments. It does not, however, exclude these rocks as sources of the oil provided its generation from them was accomplished by metamorphic agencies which began to be effective only after the deposition of the Pennsylvanian rocks.

With reference to the Chattanooga as a possible source, it is conceivable that delay in the generation of oil from it may have been due to the fact that, so far as we know, the Chattanooga in this region was not deeply buried or heavily loaded with sediments until after the thick Pennsylvanian and Permian sediments had been deposited. We know that prior to Pennsylvanian time the Chattanooga was covered by 200-400 feet of

[1]The finding of small amounts of asphaltic material at the pre-Pennsylvanian unconformity at Oklahoma City does not necessarily indicate that oil was migrating to these structures previous to Pennsylvanian time, because the Oklahoma City fold was not covered until late in Cherokee time, considerably after the disturbances of the Appalachian revolution had begun. If oil had migrated in quantity to these structures before the Pennsylvanian cover was deposited it seems that asphaltic residues should be the rule rather than the exception.

Mississippian limestones, but we do not know how much greater a thickness of Mississippian deposits may once have been present and have been stripped off during the late Mississippian peneplanation. The amount may have been small, and if so, the Chattanooga must have been lightly loaded until after the Pennsylvanian sediments became thick.

If oil is generated from the rocks merely as a result of their burial to depths of 5,000-10,000 feet without other metamorphic action, this may be a sufficient explanation of the delay in the formation of the oil from the Chattanooga. Even if this should be proved to be the true explanation, all of the theories, now so popular, requiring the generation of the oil soon after the deposition of the sediments, are still inadmissible under these conditions.

CHEROKEE SHALE AS SOURCE OF OIL

The oil obviously did not come into the Granite ridge pools in any considerable volume until after the Cherokee shales had been deposited. If it came from the Chattanooga or older rocks some mechanism such as that suggested in the foregoing paragraphs must be sought to account for its delayed appearance.

The Cherokee has generally been considered to have been an important source of oil in the Mid-Continent region; it is present on or around most of the folds under discussion; and if it was the true source, the theories which require the generation and migration of oil in the early stages soon after the deposition of the sediments need not be discarded.

If the Cherokee actually was the source of most of the oil in the pools, the following difficulties must be explained.

1. In order to reach its present reservoirs the oil must have migrated mainly downward across and through the shale which now forms the seal which traps it, because the principal accumulations are in beds below the Cherokee instead of in beds above it as would naturally be expected. At Oklahoma City (Fig. 3) the pay zones extend as much as 500 feet down into the Arbuckle limestone and are separated from each other by barren, tight streaks. At Oklahoma City, El Dorado, and a few other pools, faulting has thrown the Cherokee down against the lower rocks and some have argued that this has permitted oil from the Cherokee to gain access to the older rocks without the necessity of having migrated downward through the present seal of the pools, but such an argument does not eliminate the difficulty, because not all of the fields show such faulting. In several fields, including Cushing, Tonkawa, Peabody, Elbing, and Florence, faulting seems not to have occurred.

2. The Cherokee does not form a suitable channel for lateral migration to the structures. The enormous accumulations of oil in the pools require the contribution of oil from more than the immediate surroundings of the pool.

3. If oil had been derived from the Cherokee in quantities sufficient to have produced the great accumulations found in the Granite ridge pools it should be found, as it has not been, in pools along the whole length of the Granite ridge north of El Dorado, for the Cherokee is present in the basin everywhere on the east side of the ridge. Oil also should be much more common than it is in the top of the "Mississippi lime" throughout the Cherokee basin east of the Granite ridge, for the Cherokee is everywhere in contact with the top of that limestone, which is an eroded surface and is porous in many places.

4. In the northern pools west of the Granite ridge—Elbing, Peabody, Covert-Sellers, and Florence—the Cherokee, according to the writer's interpretation, is absent. If present at all, only the upper few feet are represented. The Marmaton beds, which constitute the basal Pennsylvanian in this locality, are variegated red, green, and yellow clays with a little chert gravel at the base, grading up into darker, marine material. They are not probable source beds for oil. Even at El Dorado and Oklahoma City only the upper part of the Cherokee is present, according to the authors who have described those fields.

If the Cherokee is thin on most, and absent around several, of the Granite ridge pools, as seems to be the fact, the argument that it has been the source of the oil is still further weakened.

5. There is no known reason for seeking a source for the "Wilcox" sand oil in the Granite ridge pools different from the source in the scattered typical "Wilcox" sand pools on the east or in the prolific pools of the Seminole uplift; but all those pools have a considerable thickness of Ordovician, Siluro-Devonian, Chattanooga and other Mississippian rocks between the sands and the Cherokee shale and they show no adequate evidence that Cherokee oil came downward to the Ordovician sands.

Considering all of the foregoing, and supplementing one line of evidence by another, we have strong reasons for thinking that the oil in the pools under discussion did not come primarily from the Cherokee shale anywhere in the vicinity of the pools.

If the oil did not come from the Chattanooga or older rocks in the vicinity of the pools and did not come from the Cherokee, whence could

it have come? It remains to examine the third possibility, namely, that it came from outside the region in which the pools are found and migrated into them.

POSSIBILITY OF DISTANT SOURCE

Let us now consider the hypothesis that the oil now in the Granite ridge pools was generated by regional metamorphism during the Appalachian revolution of Pennsylvanian-Permian time in the areas in southern and southeastern Oklahoma which were being deformed, very deeply buried, and metamorphosed at that time. Its source rocks, according to this hypothesis, might have been any or all of the strata involved in the metamorphism from which oil could be generated by metamorphic agencies. The Chattanooga shale, possibly the "Mississippi lime," various members of the Simpson formation, and perhaps the Arbuckle limestone may have contributed to the total. The quantity of oil which would be produced by the devolatilization of the rocks in southeastern Oklahoma where carbon ratios were raised must have been very great.

Migration out of the zone of generation could readily be accomplished through widespread, porous "carrier beds"[1] of which two, the sheet sands of the Simpson formation ("Wilcox" and Burgen sands) and, at least in part of the area, the weathered top of the Arbuckle limestone, were conveniently near. To a less extent, the weathered top of the "Mississippi lime" may also have served as a carrier bed, though the evidence as to the present distribution of the oil indicates the "Wilcox" as the principal carrier, with the Arbuckle as an important auxiliary.

In the disturbed areas of southeastern Oklahoma entrance of oil into the carrier beds would have been easy, especially along faults, fissures, and veins such as the grahamite veins which are fairly common in that area.[2]

The carrier beds lead from the disturbed areas to the present oil reservoirs, not only on the Granite ridge structures, but also on the Seminole uplift, and to the many "Wilcox" sand structures east of the Granite ridge pools. Furthermore, at the time when the oil migration seems to have occurred—in the Pennsylvanian, Permian, or soon thereafter and before the present westward tilting of the region—movement

[1]John L. Rich, "Function of Carrier Beds in Long-Distance Migration of Oil," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 8 (August, 1931), pp. 911-24.

[2]Joseph A. Taff, "Grahamite Deposits of Southeastern Oklahoma," *U. S. Geol. Survey Bull. 380* (1909), pp. 286-97.

north and west in the carrier beds would have been *up* a strong dip out of the basin of southeastern Oklahoma.[1]

Thus, in considering the hypothesis that the oil in the Granite ridge pools originated in the metamorphosed area in southeastern Oklahoma during the Appalachian revolution, we find adequate cause for the generation of large quantities of oil,[2] adequate carrier beds for its migration, and adequate reservoirs for its accumulation, all combined at a time which, according to all available independent evidence, was approximately the time when the oil actually was generated, migrated, and accumulated.

Furthermore, as will be explained more fully in a paper to follow, the distribution of oil in Kansas shows a distinct relation to the pre-Chattanooga outcrop of the Simpson and Arbuckle carrier beds[3] and a more marked relation to the Chautauqua-Barton arch[4] which, at the time when the oil migration is believed to have occurred, would have marked the approximate northern limit of possible migration, because oil migrating northward and westward out of the Oklahoma basin would have been trapped as it crossed that arch and, in the absence of strong artesian circulation directed northward, could not have descended into the Salina and Forest City basins north of the arch.[5]

[1]An interesting and useful study would be the reconstruction of the attitude of the "Wilcox" sand at the time of greatest sinking of the geosyncline of southeastern Oklahoma. By combining the data on the thickness of the Pennsylvanian formations with those on the present regional westward dip it should be possible to restore, approximately, the former configuration of the basin.

[2]John L. Rich, "Generation of Oil by Geologic Distillation during Mountain-Building," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 11 (November, 1927), pp. 1139-49.

[3]As shown in the paper on carrier beds already cited, oil tends to work its way up out of the carriers at every opportunity, especially where fissures have been opened by structural disturbances, and to spread out in secondary migration in the higher beds. The function of the carriers is, therefore, that of channels for long-distance migration to the region. Details of oil distribution in the higher sands are believed to be governed by the presence or absence of the carrier beds below and by local conditions which have controlled secondary migration and accumulation in the higher sands.

[4]John S. Barwick, *op. cit.*

[5]The course of the saddle between the Chautauqua arch and the Barton arch is not clearly defined. The saddle is broad and relatively flat. Its position is best shown on the map of the distribution of pre-Mississippian rocks of Kansas and Oklahoma published by McClellan (*op. cit.*), where the presence of two subsidiary arches on the broad saddle is suggested, one of them following approximately the course of the line shown in Figure 1 and the other passing farther north through southern McPherson and Marion counties.

CONCLUSIONS

Analysis of the evidence of the Granite ridge pools, considered as a whole and in relation to near-by "Wilcox" sand pools at the east and on the Seminole uplift, reveals many critical facts by which current theories of oil origin, migration, and accumulation can be judged in so far as they apply to those pools, and leads to the following tentative conclusions.

1. The Chattanooga and older rocks in the vicinity of the pools could not have been the source of the oil unless the long delay in its generation can be satisfactorily explained.

2. Many pertinent considerations indicate that the Cherokee shale in the vicinity of the pools was not the source of their oil.

3. If the arguments against a Cherokee source are granted, all of the current theories which require the deposition of the oil as oil with the sediments, or its generation relatively soon after the sediments are deposited, by the action of bacteria or other biochemical agencies, are definitely inadmissible for these pools. The same is true for theories of oil migration which depend on the agency of water squeezed out of shales by their initial compaction.

4. The theory that much of the oil may have come from the Chattanooga shale and that the delay in its appearance was due to the Chattanooga never having been heavily loaded until after Pennsylvanian and Permian sedimentation, deserves careful consideration because, if true, it indicates that loading alone, without burial to extreme depths, may be sufficient to cause the generation of oil. This theory does not fit all of the facts in the Granite ridge pools and those east and southeast, but it does not seem to be definitely excluded.

5. The hypothesis that the oil was generated by geodynamic and geothermal "cracking" of the organic source materials outside the vicinity of the present pools and migrated to them through porous carrier beds seems to accord with all of the known facts, not only in the Granite ridge pools, but also in those at the east and on the Seminole uplift. It accords also with the observations of Gish and Carr[1] which led them to believe that most of the oil originated in the Ordovician rocks. As already pointed out, however, the Ordovician acted as the carrier, but was not necessarily the source of the oil. This theory also offers a suggestive and logical explanation of the distribution of oil in Kansas as known to date.

[1]Gish and Carr, *op. cit.*

6. On the whole, the evidence strongly favors the idea that oil is generated by geodynamic and geothermal "cracking" of organic source materials in the rocks, rather than that it was deposited as oil or produced by bacterial or other biochemical changes.

DISCUSSION

JAMES H. GARDNER, Tulsa, Oklahoma (written discussion received, September 12, 1931): Mr. Rich has furnished a very interesting and valuable contribution on oil accumulation. There has been very little information heretofore in geologic literature about the time of accumulation of oil and gas on structures. But there has been considerable thought devoted to the subject and there have been many informal discussions between individuals and in meetings of geological societies in the Mid-Continent region.

Subsurface work in detail has traced the geologic history of many domes and anticlines in their relation to periods of local folding, erosion, and unconformity in deposition of sediments on and around them. In addition to such local cycles, the regional history of folding, erosion, and unconformities of overlap is continually being more clearly defined, not only in the Mid-Continent, but elsewhere. The present drilling of wells with careful sampling of rock cuttings and paleontologic determinations is producing a wealth of data on geologic history which could not have been obtained in any other way. Therefore it is timely to be discussing in printed literature what bearing these data have on the approximate, or relative, age of accumulation of oil and gas deposits in certain areas.

Concerning the area discussed, I have previously drawn the same conclusion as the one here made by Mr. Rich, to the effect that oil and gas now in the pre-Mississippian rocks were certainly accumulated in post-Mississippian time, and probably in post-Pennsylvanian time. Some geologists think they have been accumulating constantly through all the time since the earliest folding, but I seriously differ from them and find an absence of evidence of continuous accumulation for the same reason that I find evidence to the contrary on migration from a long distance.

Mr. Rich has made some logical deductions regarding the circumstances in the Granite ridge pools and it seems to me that the facts justify the conclusion that oil accumulations either are strictly local in origin or else the source is far removed. He takes the view of distant origin. In fact he postulates a nature's oil-shale refinery at a distant point of metamorphism and a transportation system, not unlike a broad pipe-line system, through "carrier beds" to the local structures. It seems to me that he is forced by his own well-reasoned analysis to a very extreme explanation and that he has overlooked important evidence against his conclusion.

We must here consider the relation of local structure and local unconformity to regional structure and regional unconformity and take note of the hiatuses of the erosion periods in order to disprove the author's theory. Let us take the Garber and Cushing district, for example, and run back the geologic calendar and strip off all subsequent strata down to the hiatus at the beginning of Chattanooga time. Here we find erosion has worked regionally to truncate and pene-

plane the pre-Chattanooga rocks down to the Arbuckle limestone of the Ordovician and older rocks so that the Chattanooga shale was deposited across them by overlap. The strike of this old buried outcrop is northwest-southeast and the strata beneath the Chattanooga dip southwest into a regional basin. The Chattanooga and higher beds seal the structural grain of the older formations below and the Simpson sands and others rise out of the basin and terminate against the bottom of the Chattanooga shale. This condition supplies an ideal trapping ground, similar to a shore line, for any oil and gas accumulations that might have come up-dip out of the basin either by differential gravity or circulating fluids through the postulated "carrier beds" of the porous Simpson sands. This structural overlap in a broad area has remained undisturbed since Chattanooga time and persisted through all subsequent "revolutions," local uplifts, and erosion periods, including the hiatus at the beginning of Pennsylvanian time and after that. The point is this: if a sufficient amount of oil and gas has risen out of the basin so that local structures by reason of their small interception of the flow have been filled thereby, the inference is that by far the major amount of oil and gas passed on by them and went ahead up-dip. The local structure would have gathered only a sample, as a barrel, with its open end to windward, would gather sand in a drifting storm. The tremendous amount of oil and gas that went ahead up-dip would have been trapped at the boundary of the "carrier beds" and would have made oil pools of regional extent. The time of the accumulation would have been any time, or all the time, since the deposition of the Chattanooga shale which sealed the old outcrop. It seems to me that this is a foregone conclusion. Such regional pools would have been so large that the intensity of past exploration in drilling could not have failed to bring them to light, for such drilling has been closely enough spaced to have defined the line where the "carrier beds" rise against the overlap. We are safe in concluding, therefore, that this assumed principle of broad accumulation was not at work in this area, and I think that the same line of deduction applies with even more potency in the salt-dome area of the Gulf Coast.

I agree with Mr. Rich in his analysis of the circumstances that seem to exclude the Chattanooga shale and the Pennsylvanian shales as local "source rocks." But I disagree with his theory of origin from distant "source rocks," and in fact I am unwilling to use the term "source rocks" except in quotation marks.

Therefore I am forced to conclude from these and other circumstances of oil and gas occurrence in local pools, that the source of oil and gas in pools, regardless of the variations of local structural conditions in which they occur, is in some way confined to the immediate area in which such pools now exist. I am further forced to conclude, on the basis of present knowledge, that the source of origin of these hydrocarbon compounds, both liquid and gaseous, and their occasional companions, helium and carbon dioxide, together with their content of rare elements and their chemical natures, are still unknown. There is strong evidence of nearly vertical migration in many pools from one stratum to another either by retention or loss of hydrostatic pressure, depending on the amount of water and its release of pressure. Some fluids and gases are too high in pressure for their depth, and some are too low. It is not exceptional to find a distinctive

oil peculiar to one structure, having approximately the same quality in strata ranging from the Permian down to the Ordovician, thus indicating a common deep source; for example, the Garber pool, Oklahoma. This indicates open cross-fracturing through beds that do not have a fractionating influence such as might be true at other places. Just how deep we may look for the source, and the re-supplying from below, of previously eroded sands with, or following, each periodic uplift, remains an open question. In some places the oil- and gas-bearing sands lie over a local structure and in others they flank a structure ranging in size from a salt plug, or a restricted, buried inlier, to the flanking of a fold like the Sabine dome. There remains, however, for serious consideration, the possibility of a source deeper than any of the strata which now contain the accumulations.

Mr. Rich has furnished an extremely interesting thesis, and is to be complimented on it, but in my opinion its chief value lies in his points of exclusion of previous theories, and I agree with him as to that part of the paper. But I do not accompany him in his journey to a far country for his "source-rock" refinery and his long transportation system. I believe that regional metamorphism has dissipated oil deposits just as it has increased the carbon ratio of coal. Whatever the origin and source may have been at a previous time, metamorphism in the mountain areas has progressed to the point of destroying oil, but I see no possibility of going there for the primary source of oil supplies now found on local structures far out in the basins. I firmly believe that separate oil-bearing structures are distinct units, and the lack of a solution of the problem of why one bears oil in large quantity and another like it in the same general district does not, indicates only our lack of information on conditions beneath and immediately surrounding them, and does not indicate the time of folding.

Many producing structures would have been too young to contain oil fields on the theory that oil migrated out of the area before they were produced. On that theory, many of the large pools on recently formed faults would not have existed, for example, the Powell-Mexia fault trend in Texas. The oil accumulations are either coincident with, or later than, the structures which contain them and this fact signifies that many of them are very recent. Accumulation coincident with each period of folding is strongly suggested in the circumstances of occurrence as well as an unknown deep-seated source.

W. B. Wilson, Tulsa, Oklahoma (written discussion received, September 16, 1931): Petroleum geologists continue to disagree more widely concerning the extent to which migration has caused oil accumulations than concerning almost any other of the unsolved problems of our profession. Recent articles have indicated that the pendulum is now swinging to the belief that migration of even a local character has played no more than a negligible part in filling reservoirs. Dr. Rich belongs to the opposition and has long stressed the probable importance of oil migration on a regional scale and in this paper he attempts a practical application of that principle.

The present writer favors a middle ground. He believes available evidence favors the conclusion that much migration may be measured in miles, but he is not willing to admit that the facts indicate the probability that oil being recovered in the El Dorado, Kansas, field ever came from the Ouachita Mountain

region. Dr. Rich does not claim that the evidence amounts to proof or that he is presenting more than a "suggested hypothesis."

In considering the oil pools of the world, one can not fail to be impressed with both their geological and geographic range. They are found in strata ranging in age from Ordovician to late Tertiary. The area that is proved or probable for oil production is certainly comparable in extent with the area in which coal is found. This widespread distribution of oil indicates a great variety of conditions under which the source materials of oil have been formed and preserved and an equally great variety of conditions under which oil may be trapped and accumulated in commercial quantities. Especially, the widespread distribution of oil indicates its origin in many local sources rather than in comparatively few centralized sources, such as the Ouachitas. If the Cherokee or Chattanooga shales are not entirely satisfactory as source beds for the oil at El Dorado, Kansas, at least their proximity to the pool favors them.

That the generation of oil is not contingent on, and perhaps not even favored by, intensive orogeny, development of high carbon ratios, et cetera, down-dip from present reservoirs, seems evident from consideration of such oil pools as those on the flanks of the Powder River and Big Horn basins of Wyoming. It is generally believed that the sources of oil from these pools have either been local or farther down in the basins. Certainly there has been no post-Cretaceous orogeny of the Ouachita type in these areas basinward from the pools. Moreover, there is no reason to believe that there has been late Tertiary orogeny in the Gulf Coast area to generate the Miocene oil so plentifully developed there. The inference is that if intensive orogeny was not needed to generate oil in the Cretaceous beds of Wyoming, or in the Tertiary beds of the Gulf Coast, neither was it required to develop oil in the Paleozoic beds of Oklahoma and Kansas.

If the source of oil in the remote Granite ridge pools was indeed in the Ouachitas, the fact should be supported by quantitative distribution of the oil. Traps in the so-called carrier beds that were nearest the Ouachitas should have been filled, and filled to overflowing, as the oil flood passed, and they should still be filled except where leakage into shallower beds or to the surface has subsequently occurred. No such conditions exist. The traps nearest the mountains are not filled to their synclines and there are many structures, such as Cromwell, that are not filled at all in the Simpson reservoirs. Instead of the Hunton arch being one giant oil field, as its proximity to the source would have favored, production there is limited to partly filled local reservoirs, a condition similar to that in more distant structural traps.

Dr. Rich's belief that the barrenness of the Beaumont and Dexter anticlines is related to the age of folding seems reasonable. However, the age of the folding in these anticlines can not be placed closer than post-Pennsylvanian and pre-Quaternary. They may very well have been folded after the western tilting of the strata away from the Ozark uplift occurred. Under such conditions the structures could not have trapped eastward-moving oil that was generated by the regional tilting and by the loading and folding in the Anadarko basin. On the contrary, the Granite ridge reservoirs would have been present to trap such oil and would have been advantageously located to do so over any structures present toward the east. It is the present writer's belief that the source of oil in the Granite ridge pools was on the west if, indeed, it

came from any far distant place. The attempt to locate the source in the Ouachitas seems to introduce more difficulties than it explains.

JOHN L. RICH (discussion received, September 28, 1931): I refer to the fifth paragraph of the discussion by Mr. Gardner. In arguing that if the oil had migrated for long distances we should find large accumulations at the up-dip margins of the older formations beneath the Chattanooga cover, Gardner is unintentionally presenting an argument in favor of such migration for, as will be shown in a forthcoming paper already referred to, on the distribution of oil in Kansas, it seems that the distribution of oil pools in Kansas corresponds in a remarkable way with the up-dip termination of the Simpson sands against the Chattanooga cover and with the regional structure caused by pre-Chattanooga arching. It is true, however, that we do not find the great and continuous pools which Gardner thinks should occur in such situations. I would seriously question his argument that in order that the producing structures should have been filled as they are, enormous quantities of oil must have passed by them up the dip. He overlooks, I think, the effect of fissured structures in gathering oil to themselves from all directions because they furnish paths for upward movement of rock fluids.[1] Also the fact should be borne in mind that the up-dip margin of the lower formations to which he refers lies in the northern part of Oklahoma, so that oil, to reach it, must have passed, and escaped being trapped by, all the structures between there and its postulated source in the southern part of the state.

The following is in reply to the discussion by Mr. Wilson. The question of the degree of orogeny, or, perhaps, of loading alone, required for the generation of oil, deserves thorough study. In the case of the Chattanooga shale as a source of the oil in the Granite ridge pools the evidence was found to indicate either (1) that the Chattanooga was *not* the source of the oil or (2) that generation of oil from it awaited the time when it became heavily loaded by later sediments.* I would question reference to the Big Horn basin as a region where orogeny has not been a factor in the generation of the oil, for the basin as a whole is located in a region which was involved in intense Rocky Mountain orogeny.

Even if oil may be generated by heavy loading without marked orogeny, we should not, it seems to me, overlook the possibility, not to say the necessity, of its having been generated in much greater quantities where, as in southern Oklahoma, strong orogenic activity accompanied by devolatilization of the sediments has occurred.

The question of the complete filling of the structures near the Ouachita Mountains is pertinent, but conclusions from that line of evidence will be open to question unless due consideration has been given to closure on the structures restored as they were at the time of the Ouachita orogeny, when the dips out of the geosynclinal basin must have been much steeper than now, and before the westward tilting of the region had occurred. In a case like that of the Cromwell pool, absence of oil in the Simpson reservoirs may mean merely that the oil escaped upward along fissures.

[1] John L. Rich, "Function of Carrier Beds in Long-Distance Migration of Oil," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 8 (August, 1931), pp. 911-24, especially pp. 918-19.

THE ASSOCIATION ROUND TABLE

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The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

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TULSA MEETING, DECEMBER 29-31, 1931

The Geological Society of America, holding its forty-fourth annual meeting, at Tulsa, Oklahoma, December 29, 30, and 31, at the invitation of the Tulsa Geological Society, has invited the Association to participate in the meeting. Registration and scientific sessions will be at the Mayo Hotel. Other organizations joining in the meeting are the Paleontological Society, the Mineralogical Society of America, the Society of Economic Geologists, and the Society of Economic Paleontologists and Mineralogists. Detailed announcements and a schedule of events have been mailed to all members and associates.

OKLAHOMA CITY MEETING, MARCH 24-26, 1932

The dates of the seventeenth annual meeting of the Association have been changed to March 24, 25, and 26, 1932, a week later than previously announced, in order to allow more time for the completion of the Oklahoma Biltmore Hotel, which has been selected as headquarters. General supervision of the convention will be in the hands of the executive committee of the Association, as usual. Local arrangements will be made by the Oklahoma City Geological Society convention committee, composed of Irving Perrine, *chairman*, W. H. Atkinson, J. T. Richards, A. H. Richards, G. C. Maddox, and Robert M.

Whiteside. The technical program is being planned by F. H. Lahee, third vice-president in charge of editorial work, Box 2880, Dallas, Texas. Papers on the geological aspects of petroleum engineering will be special features. In the miscellaneous group will be included papers on the Oklahoma City field and the East Texas field. Members planning to contribute papers should communicate with F. H. Lahee or the associate editors.

Special, reduced railroad rates will be available.

EXECUTIVE COMMITTEE MEETINGS, HOUSTON, OCTOBER 3, AND DALLAS, OCTOBER 31, 1931

The executive committee met at Houston, Texas, October 3, and at Dallas, Texas, October 31, 1931. Members present were: president L. P. Garrett, Houston; past-president Sidney Powers, Tulsa; second vice-president Frank R. Clark, Tulsa; and third vice-president F. H. Lahee, Dallas; first vice-president L. C. Decius present by proxy. Among other items, the committee made arrangements for the mid-year meeting of the Association with The Geological Society of America at Tulsa, December 29-31, 1931, and for the seventeenth annual meeting of the Association at Oklahoma City, March 24-26, 1932, changing the dates of the latter meeting to one week later than announced in previous notices, to allow time for completion of the Oklahoma City Biltmore Hotel as convention headquarters. It was agreed to print a special paper-cover separate volume of geophysical papers published in the November and December *Bulletin*. The price for this reprint is $2.00 to members and associates; $2.50 to non-members. Economies were arranged for all Association business.

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ERRATA

Page 598, line 1: "Sperry" should be *Sterry*.

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Page 872, line 3: "Cavings" should be *Cavins*.
Page 877, fourth line from bottom: "*popocapensis*" should be *potapacoensis*.
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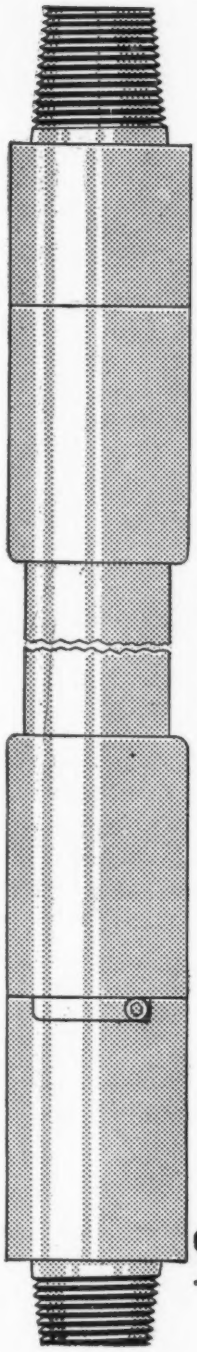

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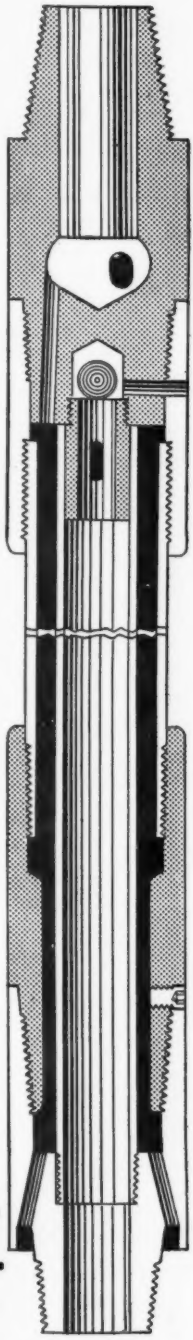

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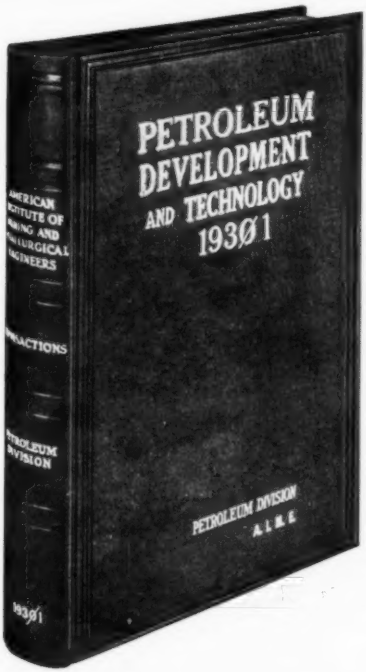

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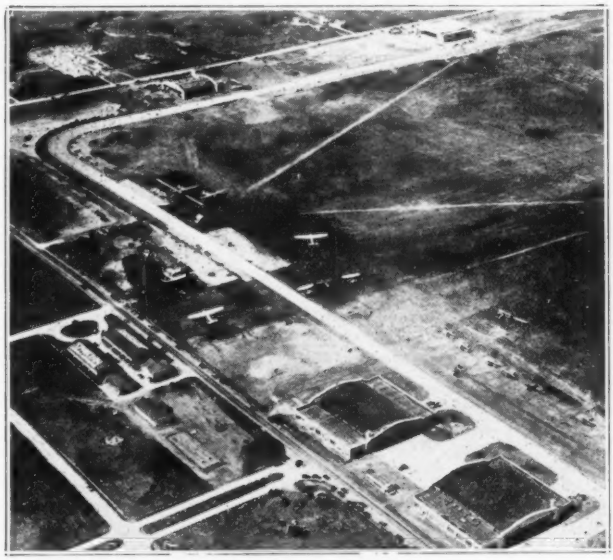

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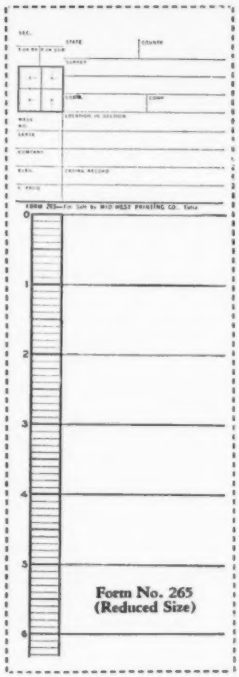

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